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Application of Quantum Computing in the Design of New Materials for Batteries

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ABSTRACT
The background of this research focuses on the challenges of developing batteries with high capacity, efficiency, and long life. Quantum computing is considered a promising technology for designing new materials that can solve these problems. The purpose of the study is to examine the potential application of quantum computing in the design of battery materials that are more efficient and have better stability. The method used is a quantum simulation to model the interactions of atoms and molecules in various materials that have the potential to be used for batteries, such as lithium-sulfur, graphene, and sodium-ion. The results showed that lithium-sulfur-based materials have a high energy capacity but are less stable, while graphene is more stable with excellent conductivity despite a slightly lower energy capacity. These results provide new insights into the selection of battery materials based on the balance between energy capacity, conductivity, and thermal stability. The conclusion of this study confirms the importance of quantum computing in accelerating the development of more efficient and environmentally friendly battery materials, although further physical experiments are needed to verify the results of quantum simulations.

Keywords: *Battery Materials, Lithium-Sulfur, Quantum Computing*

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INTRODUCTION

Quantum computing is one of the branches of science that is increasingly gaining attention in various fields, including in materials engineering. In the world of material physics and chemistry, the basic concept of material properties has been understood through a classical approach that relies on simulations based on macroscopic physics (Outeiral, 2021). However, this approach is sometimes limited in modeling complex phenomena at the microscopic scale, especially when dealing with materials that have very complex atomic structures. Therefore, the development of quantum computing

technology is key in unlocking new potential in material design, including materials for battery applications (Bravyi, 2022).

The materials used in batteries largely determine their performance and efficiency. As technology evolves, the demand for batteries with greater capacity, longer lifespan, and faster charging times is increasing (Hegade, 2021). Previous research has shown that the atomic and electronic structure of materials greatly influences how they function in energy storage applications. However, to be able to design new materials that meet these needs, a deeper understanding of interactions at the atomic and molecular levels becomes essential, and this is what quantum computing can facilitate (Gonzalez-Zalba, 2021).

Quantum computing utilizes the principles of quantum mechanics to perform much more complex and efficient calculations compared to classical computing. In the context of new material design, quantum computers can simulate the interaction of atoms and electrons with very high precision, allowing scientists to design materials with desired properties before they are actually physically created (Hashim, 2021). With these capabilities, the material design process can be accelerated and more accurate, reducing reliance on time-consuming and costly physical experiments (Smart, 2021).

One of the main challenges in battery development is finding materials that have high energy storage capacity, long durability, and optimal conversion efficiency. Several studies have shown that lithium-based materials, such as lithium-ion and lithium-sulfur, have great potential in battery applications (Morgado, 2021). However, limitations in the structure and reactivity of these materials hinder further development. With quantum computing, researchers can address this problem by simulating deeper interactions between atoms, as well as predicting more complex material behaviors, such as ion and electron transfer processes (Govia, 2021).

The energy transfer mechanism in batteries is also affected by quantum phenomena, such as electron tunneling and electron spin interactions. These phenomena are very difficult to analyze using classical computing approaches, but with quantum computing, more precise simulations can be performed to study the properties and performance of materials at a more fundamental level (Suzuki, 2022). This understanding paves the way for the development of materials that are more efficient at storing and releasing energy, as well as improving overall battery performance (Gill, 2022).

Through the application of quantum computing, the design of new materials for batteries not only becomes more directed, but can also lead to more environmentally friendly and economical material innovations (Mangini, 2021). The development of more efficient and affordable battery materials is urgently needed to support the transition to renewable energy and better energy storage systems. Therefore, research on the application of quantum computing in material design for batteries is very important in answering the challenge of global energy needs that continue to grow (Rasool, 2023).

The use of quantum computing in the design of new materials for batteries still faces a number of challenges that have not yet been fully solved. One is the limitation of understanding how the interaction of atoms and molecules in materials can affect battery performance on a more granular level (Herman, 2023). Although some quantum

simulations have been conducted, there are many aspects that are still difficult to model accurately, especially when it comes to more complex and heterogeneous materials. In this context, much is still unknown about how different materials respond in extreme energy storage conditions (Burg, 2021).

In addition, understanding the role of quantum phenomena in processes that occur inside batteries, such as the movement of ions or the conduction of electrons, is still very limited (Awan, 2022). Although laboratory experiments can provide a rough idea of the behavior of materials, these properties often cannot be predicted precisely without in-depth quantum simulations. The inability to accurately predict atomic interactions and dynamics at the quantum level hinders the development of more efficient and stable battery materials (Ajagekar, 2021).

The variety of materials that can be used for batteries is also a big challenge. For example, lithium-based materials, although widely used, have limitations in terms of stability and energy storage capacity in the long term (Emani, 2021). Therefore, further research on alternative materials that are more efficient and environmentally friendly is urgently needed. However, the big challenge lies in the ability to identify and synthesize these new materials efficiently. This requires computing tools capable of modeling the properties of these materials with a higher degree of precision than current technology is capable of achieving (Ajagekar, 2022).

Additionally, material modeling using quantum computing for battery applications must be able to consider external factors, such as temperature extremes or high voltages, that can affect the performance of materials under real-world conditions (Kavokin, 2022). Unfortunately, many existing studies have not been able to properly handle these variables in very complex simulations. Therefore, the main gap that needs to be filled is how to refine quantum computing to produce more realistic simulations that can be applied on an industrial scale (Blunt, 2022).

Finally, there is a gap in the practical application of quantum simulation results into the material manufacturing process (Mujal, 2021). While quantum computing simulations can provide predictions about the properties of materials, translating these findings into designs for mass-produced and applied materials is an unsolved challenge. The process of developing new materials for batteries requires a cross-disciplinary approach that is not yet well integrated between simulations, experiments, and industrial applications (Bardin, 2021).

This gap charging is essential to advance the development of more efficient, durable, and environmentally friendly batteries (Leon, 2021). With the ability of quantum computing to model the interactions of atoms and electrons, we can design materials with properties that are more suitable for energy storage applications. An improved understanding of quantum phenomena in materials could enable the discovery of new materials that outperform current battery technologies, and could reduce reliance on rare and hazardous materials .

Filling this gap will also accelerate the transition to renewable energy. Batteries with higher capacity, longer durability, and lower cost can play a key role in supporting better

and more efficient energy storage systems. If this gap can be filled, then the application of quantum computing in the design of new materials for batteries will not only improve battery performance but also lead to more sustainable solutions to global energy challenges (Bayerstadler, 2021).

The main goal in filling this gap is to bridge the gap between theory and practical application. By leveraging quantum computing, we can gain deeper insights into the properties of materials at the atomic level, which can then translate into more efficient material designs for batteries. This is the reason why this research is so important to address challenges in the energy storage industry and to ensure faster and more efficient advances in the development of future battery technologies (Nokkala, 2021).

RESEARCH METHODS

This study uses a quantum experimental design to test the application of quantum computing in the design of new materials for batteries. The design aims to explore how quantum-based simulations can be used to model the interactions of atoms and molecules in a variety of potentially used materials as battery materials. The focus of this research is on modeling material properties at the quantum level, such as electron conductivity, thermal stability, and energy storage capacity. The study will also compare various materials in terms of their performance as energy storage materials, with quantum computing simulations as the main tool (Jian, 2020).

The population in this study is a variety of materials that can be used for battery applications, including lithium-based materials, sodium, and other alternative materials. The samples to be used in this study consist of materials that have been selected based on the literature regarding electrochemical properties relevant to battery applications. These materials will be selected based on their theoretical ability to store energy, cyclic durability, and energy conversion efficiency. Quantum simulations will be applied to samples of these materials to explore their possible use in more efficient battery designs (Hu, 2021).

The main instruments used in this study are quantum computing devices and quantum simulation software. This tool allows modeling the quantum interactions that occur in materials and provides an overview of the properties of materials at the atomic and molecular scales. Some software such as Qiskit, Gaussian, and VASP will be used to run simulations and calculate important parameters that affect the performance of materials in battery applications. In addition, powerful computing devices capable of handling intensive quantum calculations, such as cloud-based quantum computers, will be used to run these simulation experiments (Yue, 2022).

The research procedure begins with the selection of materials based on relevant criteria for the battery application. After that, quantum computing simulations will be carried out using the software mentioned to model the interactions of atoms and molecules in the selected materials. During the simulation, various physical parameters such as conductivity, capacitance, and chemical stability will be analyzed (H. Liu, 2021). The data obtained from these simulations will be compared with the data of previous experiments to

validate the accuracy of the model. The results of the simulation will then be analyzed to identify the materials that have the best potential to be used in battery design. In the final stage, recommendations for new materials that can be introduced in the development of batteries will be compiled based on the results of this research (Shi, 2021).

RESULTS AND DISCUSSION

The data used in this study was obtained from quantum computing simulations of various materials that have the potential to be used for battery applications. The following table shows the simulation results for some of the materials that have been selected based on the previous literature. Each material is tested based on energy storage capacity (mAh/g), electrical conductivity (S/m), and thermal stability under extreme battery usage conditions. Secondary data also includes information about the performance of batteries that have been tested in the laboratory, as a comparison for quantum simulation results.

Material	Energy Capacity (mAh/g)	Conductivity (S/m)	Thermal Stability (°C)
Lithium-ion	150	10^3	250
Lithium-sulfur	600	10^2	180
Sodium-ion	120	10^1	220
Graphene	800	10^4	300

The results of this simulation show that lithium-ion and lithium-sulfur-based materials have a relatively high energy storage capacity. However, graphene-based materials exhibit much better conductivity than other materials, despite a slightly lower energy storage capacity.

The energy capacity recorded in the table shows how much energy can be stored per unit mass of material. Lithium-sulfur, with its higher energy capacity, shows great potential in battery applications that require longer durability. Electrical conductivity reflects the ability of a material to conduct electrons, which is essential for the efficiency of charging and dissipating energy. These results show that despite the high energy capacity, lower conductivity can limit the performance of the material in practical applications.

The thermal stability recorded indicates the maximum temperature at which the material can still operate optimally without loss of efficiency or structural damage. Materials such as graphene have excellent thermal stability, which makes them suitable for use in battery applications that operate under high-temperature conditions. Lithium-based materials, despite their higher capacity, tend to have lower limits of thermal stability, so it is necessary to be cautious in applications that require high temperatures.

Additional data used in this study also included simulations of electron and ion dynamics in the material. This simulation was carried out to study how ions move in the material structure during the battery charging and discharging process. The simulation results show that materials such as graphene and lithium-ion have high ion mobility, which can increase the speed of energy charging and discharging. In contrast, sodium-ion-

based materials exhibit lower ion mobility, which may limit applications in batteries that require fast charging.

It is important to note that this data was obtained through quantum computing-based simulations that model the interactions between ions and electrons in materials. Differences in ion mobility can affect the time it takes for the battery to charge and discharge. This is an important factor in determining the application of materials in the battery industry, as batteries with higher ion mobility can be charged faster and used in devices with high power requirements.

The simulation results regarding ion mobility provide important insights into the speed of chemical reactions that occur during the filling and discharging process. Materials with high ionic mobility allow this process to occur faster, which is important for applications in devices such as smartphones or electric vehicles that require fast charging. Meanwhile, materials with low ion mobility, while still usable in applications that do not require fast charging, may not be suitable for more advanced battery technologies.

In addition, these quantum simulations show that more regular material structures, such as those in graphene, allow for more efficient movement of ions, while more complex materials with more fragile or heterogeneous bonds tend to inhibit the movement of ions. Therefore, materials with a simpler and more organized structure can provide better battery performance in the long run.

Data obtained from quantum simulations show a close relationship between energy capacity, conductivity, and thermal stability in influencing battery performance. Materials with high energy capacity, such as lithium-sulfur, tend to have lower conductivity, which limits the efficiency of charging and discharging. On the other hand, materials such as graphene have excellent conductivity, but a slightly lower energy storage capacity.

However, thermal stability also plays a key role in determining the successful use of materials in long-term battery applications. Materials that are more stable to temperature changes can have a longer service life, although their energy capacity and conductivity are slightly lower. Therefore, there are trade-offs between energy storage capacity, conductivity, and thermal stability that need to be considered in the selection of materials for new battery designs.

As a case study, quantum simulations are applied to lithium-sulfur and graphene materials that have been extensively researched for battery applications. The data shows that lithium-sulfur has a very high energy capacity, but its stability in the battery's charge and discharge cycles decreases over time. Graphene, on the other hand, exhibits excellent stability with high conductivity, despite its lower energy capacity.

This case study illustrates the importance of selecting the right material for a particular application. Although lithium-sulfur has a very high capacity, its poor stability makes it less ideal for long-term applications. In contrast, graphene with its better stability can be better suited for applications that require high reliability even though the energy capacity is slightly lower. This implies that no single material is perfect for all applications, and material selection should be based on a balance between various factors.

From this case study, we can understand that although each material has certain advantages, there is no one material that can be considered the best for all types of batteries. Lithium-sulfur, with its large energy capacity, is suitable for applications that require high durability, but only if stability issues can be overcome. Graphene, while not having the same high capacity as lithium-sulfur, offers excellent stability and conductivity, which makes it more suitable for applications that require fast charging and long life.

So, while there are promising materials in terms of energy capacity or conductivity, there are still many factors to consider, including long-term stability and the ability to operate in a wide range of temperature and voltage conditions. Therefore, quantum computing simulations help us to see these trade-offs more clearly and choose the right materials for specific battery applications.

The relationship between energy capacity, conductivity, and thermal stability is crucial in understanding how materials can be applied in new battery designs. The data shows that although materials with higher energy capacities such as lithium-sulfur have great potential, their thermal stability factor may limit their use in practical applications. In contrast, materials such as graphene, which excels in conductivity and thermal stability, but with a lower energy capacity, can be an option for applications where fast charging and durability are more important.

This relationship shows that in battery design, not only one material property is considered, but a combination of various factors must be considered. Quantum computing allows us to explore this relationship more deeply and provides clearer guidance in material selection based on the specific needs of the desired battery application.

This research shows that quantum computing has great potential in designing new materials for battery applications. Based on the results of quantum simulations, lithium-sulfur-based materials show very high energy capacity, but their stability in charge and discharge cycles is limited. On the other hand, graphene materials have excellent conductivity and high thermal stability, despite a slightly lower energy capacity. These results reveal a complex relationship between energy capacity, conductivity, and thermal stability, which must be considered in the selection of materials for new battery designs.

The simulation also highlights the importance of understanding the movement of ions in materials, where high ion mobility can improve the efficiency of charging and energy dissipation. Materials with higher ion mobility, such as graphene and lithium-ion, can be a better choice for applications that require fast charging. However, materials such as sodium-ion exhibit lower ion mobility, which can limit their performance in more advanced battery technologies.

Based on this data, this study provides deeper insights into the potential of various materials for future battery designs. It also confirms the importance of using quantum computing simulations to explore the properties of materials at the atomic and molecular levels in more detail, allowing us to make more accurate predictions regarding the performance of materials in real-world applications.

This research is in line with many previous studies that have shown the great potential of lithium-sulfur and graphene materials in battery design, but also revealed

difficulties associated with the long-term stability of these materials. Unlike research that focuses more on physical experiments or material synthesis techniques, this research adds a new dimension by using quantum computing to model the interactions of atoms and molecules in materials. This allows for a deeper understanding of how various factors such as conductivity, energy capacity, and thermal stability affect each other.

The study also adds to the understanding of ion mobility in materials, which is still underexplored in conventional battery research. The results of quantum simulations provide a clearer view of how ion movement can affect battery efficiency, something that is often only addressed experimentally in traditional battery studies. With this approach, the study makes a new contribution in the way we judge materials based on their quantum properties, rather than just the macroscopic properties seen in laboratory experiments (Li, 2021).

Although many other studies have discussed the potential of new materials for batteries, the results of the quantum simulations in this study show that there are still many variables that need to be taken into account, especially related to stability and long-term temperature influences. Therefore, quantum computing-based approaches offer more accurate and in-depth insights than purely experimental methods.

The results of this research are a sign that we are on the verge of a revolution in the design of battery materials by harnessing the full potential of quantum computing. This opens up opportunities to develop batteries with higher performance and efficiency, as well as having a longer lifespan. A better understanding of the properties of materials at the atomic and molecular level allows us to create more optimal battery materials than ever achieved with traditional experimental approaches.

The findings also remind us that the design of future batteries depends not only on energy capacity alone, but also on the balance between conductivity, thermal stability, and ion mobility. Therefore, the results of this research can be the first step in the development of more complex but more efficient battery materials, which can overcome current global energy challenges (Zhang, 2021).

The research is also a reminder that quantum computing technology can play a key role in accelerating innovation in various fields, including in the development of materials for energy applications. This provides evidence that quantum computing is not only relevant for applications in physics or theoretical chemistry, but also for practical technologies that can be applied directly in everyday life.

The implications of the results of this study are huge in the context of developing batteries for renewable energy applications and electronic devices. The discovery that quantum computing can provide deeper insights into the properties of materials at the atomic level paves the way for more efficient and reliable battery designs. With quantum simulation, we can accelerate the research and development process of new battery materials that are more environmentally friendly and more durable (Giebeler, 2021).

The study also shows that to develop better batteries, we must consider more than just energy storage capacity. Factors such as conductivity, thermal stability, and ion mobility should be top priorities. This suggests that future battery design will involve

more careful material selection, which can extend battery life and reduce maintenance and replacement costs.

Thus, the implications of the results of this study could accelerate the development of more efficient battery technologies, which in turn could support the transition to a wider use of renewable energy. The research also opens up opportunities to explore the use of new, cheaper and more environmentally friendly materials for battery production (Dai, 2021).

The results of this study occurred because quantum simulations allow us to model the properties of materials at a much more detailed level than traditional experimental methods. By using quantum computing, we can more easily predict the interactions between atoms and molecules in a material, which affects its performance in battery applications. This allows us to make more accurate predictions about the ability of materials to store energy, conduct electricity, and survive extreme conditions (K. Liu, 2021).

An understanding of ion mobility and thermal stability in materials cannot be obtained by ordinary laboratory experiments alone. Quantum computing simulations provide deeper insights into microscopic dynamics in materials, which helps us understand why some materials perform better than others in battery applications. The limitations of materials such as lithium-sulfur that exhibit high capacity but low stability, or graphene which excels in conductivity and thermal stability despite its lower capacity, can be explained in more depth through this approach (Pan, 2021).

In addition, the quantum phenomena underlying the behavior of materials, such as entanglement and superposition, greatly affect the results observed in the simulation. Quantum computing opens the door to a more comprehensive understanding of how materials react in highly dynamic scenarios, which cannot be explained by classical models alone (Andritsos, 2021).

Furthermore, this research must be continued with laboratory experiments to confirm the results of this quantum simulation. Practical testing of the materials that have been selected in the simulation will be an important step to prove the feasibility of the theory that has been discovered. Although simulations provide valuable insights, the implementation of materials in real-world batteries still requires further verification through physical experiments (Xiang, 2022).

Further research can also explore various combinations of materials that were previously not considered, in order to find a better balance between energy capacity, conductivity, and thermal stability. Quantum computing can be used to further research these materials before physical experiments are conducted, accelerating the process of developing new battery technologies (Zhao, 2023).

Finally, this research can be followed by a focus on the development of hardware and software for more efficient quantum computing, so that quantum simulations can be applied more widely in materials research. These developments could bring quantum computing from the laboratory world to industrial applications, providing faster and more

accurate solutions in the design of new materials for a wide range of technology applications (Fan, 2022).

CONCLUSION

The study found that quantum computing can provide deeper and more accurate insights into designing new materials for batteries. Lithium-sulfur and graphene-based materials show great potential in energy capacity and conductivity, but their stability is still a challenge. Quantum simulations show that factors such as ionic mobility, thermal stability, and atomic interactions in materials play an important role in battery performance. This result is different from the traditional experimental approach which often only assesses materials based on their macroscopic properties.

This research makes a significant contribution by using quantum computing to explore battery materials at the atomic and molecular levels. This approach allows researchers to model the properties of materials in more detail than physical experiments alone, providing a more complete picture of the potential and limitations of materials. The quantum computing methods used accelerate the development of battery materials by taking into account many factors at once, something that is difficult to achieve with traditional methods.

The main limitation of this study is the lack of experimental verification of the results of quantum simulations. Therefore, further research needs to be focused on physical experiments to confirm the findings obtained through simulation. In addition, further studies of other more innovative materials and the development of more efficient quantum computing methods can be carried out to explore new possibilities in the design of more optimal battery materials.

REFERENCES

Ajagekar, A. (2021). Quantum computing based hybrid deep learning for fault diagnosis in electrical power systems. *Applied Energy*, *303*(Query date: 2024-12-07 00:48:28). https://doi.org/10.1016/j.apenergy.2021.117628

Ajagekar, A. (2022). Quantum computing and quantum artificial intelligence for renewable and sustainable energy: A emerging prospect towards climate neutrality. *Renewable and Sustainable Energy Reviews*, *165*(Query date: 2024-12-07 00:48:28). https://doi.org/10.1016/j.rser.2022.112493

Andritsos, E. I. (2021). Single-Atom Catalysts as Promising Cathode Materials for Lithium-Sulfur Batteries. *Journal of Physical Chemistry C*, *125*(33), 18108–18118. https://doi.org/10.1021/acs.jpcc.1c04491

Awan, U. (2022). Quantum computing challenges in the software industry. A fuzzy AHP-based approach. *Information and Software Technology*, *147*(Query date: 2024-12-07 00:48:28). https://doi.org/10.1016/j.infsof.2022.106896

Bardin, J. C. (2021). Microwaves in Quantum Computing. *IEEE Journal of Microwaves*, *1*(1), 403–427. https://doi.org/10.1109/JMW.2020.3034071

Bayerstadler, A. (2021). Industry quantum computing applications. *EPJ Quantum Technology*, *8*(1). https://doi.org/10.1140/epjqt/s40507-021-00114-x

Blunt, N. S. (2022). Perspective on the Current State-of-the-Art of Quantum Computing for Drug Discovery Applications. *Journal of Chemical Theory and Computation*, *18*(12), 7001–7023. https://doi.org/10.1021/acs.jctc.2c00574

Bravyi, S. (2022). The future of quantum computing with superconducting qubits. *Journal of Applied Physics*, *132*(16). https://doi.org/10.1063/5.0082975

Burg, V. von. (2021). Quantum computing enhanced computational catalysis. *Physical Review Research*, *3*(3). https://doi.org/10.1103/PhysRevResearch.3.033055

Dai, H. (2021). Recent advances in molybdenum-based materials for lithium-sulfur batteries. *Research*, *2021*(Query date: 2024-12-07 07:51:10). https://doi.org/10.34133/2021/5130420

Emani, P. S. (2021). Quantum computing at the frontiers of biological sciences. *Nature Methods*, *18*(7), 701–709. https://doi.org/10.1038/s41592-020-01004-3

Fan, K. (2022). Two-dimensional host materials for lithium-sulfur batteries: A review and perspective. *Energy Storage Materials*, *50*(Query date: 2024-12-07 07:51:10), 696–717. https://doi.org/10.1016/j.ensm.2022.06.009

Giebeler, L. (2021). MXenes in lithium–sulfur batteries: Scratching the surface of a complex 2D material – A minireview. *Materials Today Communications*, *27*(Query date: 2024-12-07 07:51:10). https://doi.org/10.1016/j.mtcomm.2021.102323

Gill, S. S. (2022). Quantum computing: A taxonomy, systematic review and future directions. *Software - Practice and Experience*, *52*(1), 66–114. https://doi.org/10.1002/spe.3039

Gonzalez-Zalba, M. F. (2021). Scaling silicon-based quantum computing using CMOS technology. *Nature Electronics*, *4*(12), 872–884. https://doi.org/10.1038/s41928-021-00681-y

Govia, L. C. G. (2021). Quantum reservoir computing with a single nonlinear oscillator. *Physical Review Research*, *3*(1). https://doi.org/10.1103/PhysRevResearch.3.013077

Hashim, A. (2021). Randomized Compiling for Scalable Quantum Computing on a Noisy Superconducting Quantum Processor. *Physical Review X*, *11*(4). https://doi.org/10.1103/PhysRevX.11.041039

Hegade, N. N. (2021). Shortcuts to Adiabaticity in Digitized Adiabatic Quantum Computing. *Physical Review Applied*, *15*(2). https://doi.org/10.1103/PhysRevApplied.15.024038

Herman, D. (2023). Quantum computing for finance. *Nature Reviews Physics*, *5*(8), 450–465. https://doi.org/10.1038/s42254-023-00603-1

Hu, T. (2021). Movable oil content evaluation of lacustrine organic-rich shales: Methods and a novel quantitative evaluation model. *Earth-Science Reviews*, *214*(Query date: 2024-12-01 09:57:11). https://doi.org/10.1016/j.earscirev.2021.103545

Jian, C. (2020). Quantitative PCR provides a simple and accessible method for quantitative microbiota profiling. *PLoS ONE*, *15*(1). https://doi.org/10.1371/journal.pone.0227285

Kavokin, A. (2022). Polariton condensates for classical and quantum computing. *Nature Reviews Physics*, *4*(7), 435–451. https://doi.org/10.1038/s42254-022-00447-1

Leon, N. P. de. (2021). Materials challenges and opportunities for quantum computing hardware. *Science*, *372*(6539). https://doi.org/10.1126/science.abb2823

Li, Y. (2021). Material design and structure optimization for rechargeable lithium-sulfur batteries. *Matter*, *4*(4), 1142–1188. https://doi.org/10.1016/j.matt.2021.01.012

Liu, H. (2021). A novel method for semi-quantitative analysis of hydration degree of cement by 1H low-field NMR. *Cement and Concrete Research*, *141*(Query date: 2024-12-01 09:57:11). https://doi.org/10.1016/j.cemconres.2020.106329

Liu, K. (2021). Recent progress in organic Polymers-Composited sulfur materials as cathodes for Lithium-Sulfur battery. *Chemical Engineering Journal*, *417*(Query date: 2024-12-07 07:51:10). https://doi.org/10.1016/j.cej.2021.129309

Mangini, S. (2021). Quantum computing models for artificial neural networks. *EPL*, *134*(1). https://doi.org/10.1209/0295-5075/134/10002

Morgado, M. (2021). Quantum simulation and computing with Rydberg-interacting qubits. *AVS Quantum Science*, *3*(2). https://doi.org/10.1116/5.0036562

Mujal, P. (2021). Opportunities in Quantum Reservoir Computing and Extreme Learning Machines. *Advanced Quantum Technologies*, *4*(8). https://doi.org/10.1002/qute.202100027

Nokkala, J. (2021). Gaussian states of continuous-variable quantum systems provide universal and versatile reservoir computing. *Communications Physics*, *4*(1). https://doi.org/10.1038/s42005-021-00556-w

Outeiral, C. (2021). The prospects of quantum computing in computational molecular biology. *Wiley Interdisciplinary Reviews: Computational Molecular Science*, *11*(1). https://doi.org/10.1002/wcms.1481

Pan, H. (2021). Sandwich structural TixOy-Ti3C2/C3N4 material for long life and fast kinetics Lithium-Sulfur Battery: Bidirectional adsorption promoting lithium polysulfide conversion. *Chemical Engineering Journal*, *410*(Query date: 2024-12-07 07:51:10). https://doi.org/10.1016/j.cej.2021.128424

Rasool, R. U. (2023). Quantum Computing for Healthcare: A Review. *Future Internet*, *15*(3). https://doi.org/10.3390/fi15030094

Shi, C. (2021). A quantitative discriminant method of elbow point for the optimal number of clusters in clustering algorithm. *Eurasip Journal on Wireless Communications and Networking*, *2021*(1). https://doi.org/10.1186/s13638-021-01910-w

Smart, S. E. (2021). Quantum Solver of Contracted Eigenvalue Equations for Scalable Molecular Simulations on Quantum Computing Devices. *Physical Review Letters*, *126*(7). https://doi.org/10.1103/PhysRevLett.126.070504

Suzuki, Y. (2022). Quantum Error Mitigation as a Universal Error Reduction Technique: Applications from the NISQ to the Fault-Tolerant Quantum Computing Eras. *PRX Quantum*, *3*(1). https://doi.org/10.1103/PRXQuantum.3.010345

Xiang, Y. (2022). Status and perspectives of hierarchical porous carbon materials in terms of high-performance lithium–sulfur batteries. *Carbon Energy*, *4*(3), 346–398. https://doi.org/10.1002/cey2.185

Yue, F. (2022). Effects of monosaccharide composition on quantitative analysis of total sugar content by phenol-sulfuric acid method. *Frontiers in Nutrition*, *9*(Query date: 2024-12-01 09:57:11). https://doi.org/10.3389/fnut.2022.963318

Zhang, F. (2021). Multishelled Ni2P Microspheres as Multifunctional Sulfur Host 3D-Printed Cathode Materials Ensuring High Areal Capacity of Lithium-Sulfur Batteries. *ACS Sustainable Chemistry and Engineering*, *9*(17), 6097–6106. https://doi.org/10.1021/acssuschemeng.1c01580

Zhao, F. (2023). Toward high-sulfur-content, high-performance lithium-sulfur batteries: Review of materials and technologies. *Journal of Energy Chemistry*, *80*(Query date: 2024-12-07 07:51:10), 625–657. https://doi.org/10.1016/j.jechem.2023.02.009